NACA

RESEARCH MEMORANDUM

SPARK IGNITION OF FLOWING GASES

V - APPLICATION OF FUEL-AIR-RATIO AND INITIAL-

TEMPERATURE DATA TO IGNITION THEORY

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
November 1, 1955

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SUMMARY

Research was conducted to show the effect of fuel-air ratio and initial temperature on spark-ignition energy and to apply these results to a previously developed theory of ignition. Data were obtained at a pressure of 5.0 inches mercury absolute, gas velocity of 50 feet per second, low-turbulent flow condition, and with long-duration spark discharges.

Over a range of initial temperatures (80° to 250° F), experimental ignition energies decreased with an increase in temperature in agreement with the previously developed theoretical relationship. Ignition energies first decreased and then increased with increasing fuel-air ratio and did not entirely agree with the theoretical relationship. The fuel-air ratio data were correlated by applying an empirical correction factor; the correction factor was a function of the mole fraction of the fuel in the igniting mixture. Ignition time delay and cathode energy losses were considered as possible reasons for lack of agreement between theoretical and experimental effects of fuel-air ratio.

INTRODUCTION

The research reported herein is part of a program being conducted at the NACA Lewis laboratory to provide fundamental information on ignition and combustion applicable to the design and operation of jet-engine combustors.

A previous report (ref. 1) presented a theory of spark ignition in nonturbulent and turbulent flowing gases using long-duration discharges. This theory is based on thermal processes and relates the spark discharge energy with gas density and velocity, electrode spacing, spark duration, intensity of turbulence, and constants of the fuel. A limited amount of ignition data obtained with varying pressure, velocity, spacing, spark duration, and intensity of turbulence substantiated the relation at one fuel-air ratio.

Further experimental proof of the theory was desired inasmuch as other investigators have shown large discrepancy between experiment and theory under certain conditions. For example, reference 2 shows that in lean mixtures experimental and theoretical energies are comparable; in rich mixtures calculated energies are many times larger than experimental energies. The purpose of the present research was twofold: (1) To show the effects of fuel-air ratio and initial temperature on energy requirements, and (2) to apply these results to the theory developed in reference 1.

The effects of initial temperature and fuel-air ratio on the spark energy required for ignition of homogeneous propane-air mixtures were determined under low-turbulent flow conditions at a pressure of 5.0 inches mercury absolute and a gas velocity of 50 feet per second using long-duration spark discharge. The application of these data to theoretical equations relating spark energy to operating variables is presented.

APPARATUS AND PROCEDURE

The flow apparatus of references 1 and 3, with the addition of an electric heater to heat the incoming air, was used for this investigation. The heater was installed just downstream of the air orifice (fig. 1). All tests were run with the electrodes located 4 inches downstream from the inlet to the test section. A fine screen (approx. 50 mesh) was installed at the inlet. With this arrangement, the intensity of turbulence was about 0.8 percent (ref. 1).

The ignition system produced a single spark having a duration of approximately 500 microseconds and an exponential decay of current. The energy of the spark was measured by oscillographic techniques that gave voltage and current of the discharge as a function of time. The electrodes were shanks from no. 74 high-speed drills (0.0225-in. diam.) and were located on a center line perpendicular to the direction of flow.

The procedure used was first to establish the proper flow conditions and then to locate the minimum ignition point by trial and error. A more detailed description of the procedure used to obtain the ignition data is presented in reference 4.

RESULTS

Initial-Temperature Effect

The effect of initial temperature on the ignition energy requirement is shown in figure 2; the energy required decreased somewhat with an increase in temperature. This trend has been established elsewhere in the literature (ref. 5).

The data were applied to the following nonturbulent-flow equation from reference 1:

$$\frac{4\pi JV\theta kc_p(T_f - T_o)^2}{CHQN_fN_o\rho Ae^{-\frac{E}{RT_f}}} = \ln\left(\frac{2V\theta + S}{S}\right) \tag{1}$$

where

J   conversion factor, heat to electrical energy

V   gas velocity

θ spark duration

k   thermal conductivity

c_p specific heat

T_f flame temperature

T_o initial temperature

C   constant

H   total energy of the spark discharge

Q   heat of combustion of fuel

N_f mole fraction of fuel

N_o mole fraction of oxygen

ρ density at flame temperature

A   constant

E   energy of activation

R   gas constant

S   electrode spacing

For constant pressure, velocity, spark duration, fuel-air ratio, electrode spacing, and $\rho \propto 1/T_f$ it can be shown that,

$$\ln \frac{H}{kc_p T_f (T_f - T_o)^2} = C_1 + C_2 \left(\frac{1}{T_f}\right) \tag{2}$$

where

$$C_2 = \frac{E}{R}$$

The flame temperature can be expressed in terms of the initial temperature by the approximate relation that flame temperature increases by 1/2 the increase in initial temperature (ref. 5); that is, if the initial temperature increases 100° F, the flame temperature increases 50° F.

Equation (2) then becomes

$$\ln \frac{H}{kc_p \left(1962 + \frac{1}{2} T_o\right)\left(1962 - \frac{1}{2} T_o\right)^2} = C_1 + C_3 \frac{1}{1962 + \frac{1}{2} T_o} \tag{3}$$

For the data obtained in this investigation, the relation of equation (3) is shown in figure 3. Thermal-conductivity and specific-heat values were determined for unburned mixture at flame temperature. Flame temperatures were theoretical adiabatic temperatures. In the temperature range investigated (80° to 250° F) the straight-line relation of the data shows that a reasonable agreement exists between the experimental data and the theory developed in reference 1. The activation energy E can be calculated from the slope of the curve. However, the range of initial temperatures investigated is too small and the data too scattered to give a slope that can be used to calculate activation energy precisely.

Fuel-Air-Ratio Effect

The variation in ignition energy requirements with fuel-air ratio determined at one pressure, velocity, spark-duration, electrode-spacing, and temperature condition is shown in figure 4. The smoothness of the data was quite good except in a small region around a fuel-air ratio of 0.095. There may be a break in the curve at this point so that two lobes (dashed curve in fig. 4) could be drawn. Such lobes have been observed in flammability limit investigations with quiescent mixtures (ref. 6). However, the trend is small and no great significance is attached to the result in the present work.

For the variable fuel-air ratio data, equation (1) becomes

$$\frac{H N_f N_o \ln \frac{2V\theta + S}{S}}{T_f (T_f - T_o)^2} = C_4 + C_2 \left(\frac{1}{T_f}\right) \tag{4}$$

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The ignition data for fuel-air ratios from 0.045 to 0.105 of figure 4,
together with calculated adiabatic flame temperatures, were applied to
this equation. Flame temperatures were calculated only to a fuel-air
ratio of 0.105 at which the temperature was approximately equal to that
at fuel-air ratio of 0.045. The resulting relation is plotted in figure
5. A single straight-line relation predicted by theory was not obtained.
There is a factor of about 2 between the rich and lean ends of the data.
Activation energies as calculated from the slopes of the straight portions
of the curve were 45.3 kilocalories per mole for the upper line and 25.8
kilocalories per mole for the lower line.

DISCUSSION

The theory of reference 1 shows a relation among the variables of
total spark-discharge energy, gas density and velocity, electrode spacing,
spark duration, intensity of turbulence, and fuel constants. The data
showing the effects of initial temperature and fuel-air ratio were applied
to this theory. The results show that the effect of temperature was con-
sistent with the theory. However, the effect of fuel-air ratio was such
that either the lean data or the rich data, but not both, could be con-
sistent with the theory depending upon choice of value for E. Other
investigators have encountered this same difficulty with fuel-air ratio.
Reference 2 describes an ignition theory that is separate and distinct
from that of reference 1, but nevertheless, is based on thermal processes.
This reference shows that there is discrepancy between theory and experi-
ment for the fuel-air ratio data. This discrepancy will now be compared
with that found with the present work.

The ratios of theoretical to experimental energy were calculated
from the data and theory of reference 2. The same calculation of theo-
retical to experimental energy was made for the data contained in this
report. (The term

$$\frac{4\pi JV\theta kc_p(T_f - T_o)^2}{CHQN_fN_o\rho Ae^{-\frac{E}{RT_f}}\ln\left(\frac{2V\theta + S}{S}\right)}$$

derived from equation (1) represents the ratio of theoretical to experi-
mental energy.) For the calculation k and c_p were assumed constant
and a value of 26 kilocalories per mole was used for E. The energy
ratios determined by the separate theories and data were multiplied by
constants in order to adjust the energy ratios to 1 at a fuel-air ratio
of approximately 0.045. The adjusted data are plotted against fuel-air
ratio in figure 6. Both theories give results that deviate in the same
direction, and they cannot be used to predict trends exactly. The theory
of reference 1 is somewhat better in predicting trends throughout the
whole fuel-air-ratio range.

In an effort to explain the discrepancy between the theoretical and experimental results, an empirical relation that might show the factors needed to correlate the data was determined. It was found that multiplying the original equation (1) by $1 - \dfrac{0.02}{N_f}$ gave a reasonable correlation, as shown in figure 7. The activation energy as determined from the slope of the curve was 28.4 kilocalories per mole which is within the limits (26 to 38 kilocalories per mole) used in the literature (refs. 7 and 8). Hence, further consideration was given as to how N_f, the mole fraction of fuel, might enter into the theory.

If the correction term used to correlate the data (fig. 7) acts on the energy H, then the factor $H\left(1 - \dfrac{0.02}{N_f}\right)$ or $H - \dfrac{0.02H}{N_f}$ would be involved. This would indicate the possibility of an energy loss before ignition occurs dependent on the total energy and on fuel concentration. The energy loss would be by heat conduction and should depend on temperature and time. Considering the heated zone left by the spark, the temperature of the zone should be roughly dependent on H. The term $1/N_f$ can represent time if ignition time lag varies with N_f as described in reference 9. When separately heated streams of propane and air were mixed together, there was a time lag to ignition that was inversely proportional to N_f. However, whether time lag concept can be applied to this problem in this manner is questionable for two reasons. In the first place, the theory considers the heated zone left by the spark as being at or near flame temperature so that time lag should be insignificant. Also, since time lag is affected by pressure (ref. 10), a pressure term that might or might not destroy previous correlations must be included. Additional experiments would be required to prove or disprove this concept.

The mole fraction of fuel N_f might also affect the energy requirements by affecting the portion of energy dissipated in the region near the cathode electrode. (For discussion of cathode drop region, see ref. 3.) The energy in the cathode region H_c is an appreciable part of the total energy and is dissipated so close to the electrode that it is probably unavailable for the ignition process. If this is the case then the actual energy available for ignition is $H - H_c$ or $H\left(1 - \dfrac{H_c}{H}\right)$ instead of H. The discrepancy between theoretical and experimental results could be accounted for, if the energy ratio term H_c/H varied inversely with N_f to a sufficient degree. As shown in the appendix, the energy ratio does decrease with an increase in N_f; however, the decrease is only about 20 percent. While this correction for cathode energy would improve the correlation somewhat (fig. 5), a much larger factor is needed.

There are probably other factors that may be responsible for the observed discrepancy. Preferential diffusion of the deficient reactant

in the combustible mixture could be a contributing factor as discussed in conjunction with the ignition theory (ref. 2). Or possibly some cool flame mechanism that results in lower activation energy may be present. Both of these items are qualitatively in the right direction to account for the difference between the rich and lean data. Actually, it may be that a combination of factors discussed is responsible for the discrepancy. Quantitative data on these factors would necessitate research beyond the scope of this report.

SUMMARY OF RESULTS

The following results were obtained in the investigation to show the effect of fuel-air ratio and initial temperature on spark-ignition energy and to apply these data to an ignition theory developed in a previous report:

1. Over a range of initial temperatures ($80°$ to $250°$ F) ignition energy decreased with an increase in temperature; the data agreed with previously developed theoretical relations.

2. Ignition energy first decreased and then increased with an increase in fuel-air ratio. This effect was such that either the lean or the rich data, but not both, could be consistent with the theory depending on choice of value for activation energy. All the fuel-air-ratio data were correlated by applying an empirical correction factor to the theoretical relation. This correction factor was a function of the mole fraction of the fuel in the igniting mixture.

3. Ignition time lag and cathode energy losses were considered as possible reasons for the lack of agreement between theoretical and experimental effects of fuel-air ratio.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, September 19, 1955

APPENDIX - EFFECT OF FUEL CONCENTRATION ON RATIO OF

CATHODE ENERGY TO TOTAL SPARK ENERGY

Cathode voltage drop and energy loss in the cathode drop region of a spark discharge are discussed in reference 3. The method used in the reference to determine cathode voltage drop and energy is as follows: A family of voltage against current traces was obtained at various electrode spacings and constant-current cross plots of the data were made. These cross plots show a linear increase in voltage with increasing spacing. Extrapolation of the lines to zero spacing gave cathode drop as a function of current. Cathode energies were calculated from the cathode drop, current, and time data.

The data of reference 3 were obtained at low velocity so the discharge was not blown appreciably downstream. In the present investigation, a flow velocity of 50 feet per second was used resulting in the spark being blown an appreciable distance downstream. The spark lengthened with time and, in making constant-current cross plots, it was necessary to determine its actual length.

An example of the procedure used is shown in figure 8. The voltage-current characteristics of five sparks taken at different electrode spacings are plotted (fig. 8(a)) along with a curve showing time after the discharge starts. Values of voltage at constant current were taken from the curves and plotted (fig. 8(b)) against the length of the discharge at that instant of time. The length of the discharge was calculated (ref. 1) as $S + 2Vt$ where t is the time corresponding to the value of current used. Extrapolation of the curves to zero length gives intercepts representing cathode drops at various currents. The cathode drop data are shown in figure 8(a). Cathode energies were then calculated from the cathode drops, current, and time data.

The ratio of cathode energies to total ignition energies for 3 fuel-air ratio conditions is plotted in figure 9. Cathode energy ratios are calculated by two methods: the one described herein and the one used in reference 3 for low-velocity data. It is believed that the correct curve lies between these limits and would be nearer the higher-velocity curve. The data for low-velocity flow should be too low assuming the cathode drop is not affected by velocity; whereas, the high-velocity curve might be too high due to the discharge being distorted (shortened) from the shape assumed by the theory. The curves show less energy entering the cathode region in rich mixtures than in lean mixtures. At higher velocities there is approximately a 20 percent decrease in the energy ratio as the concentration is increased from 0.029 to 0.062.

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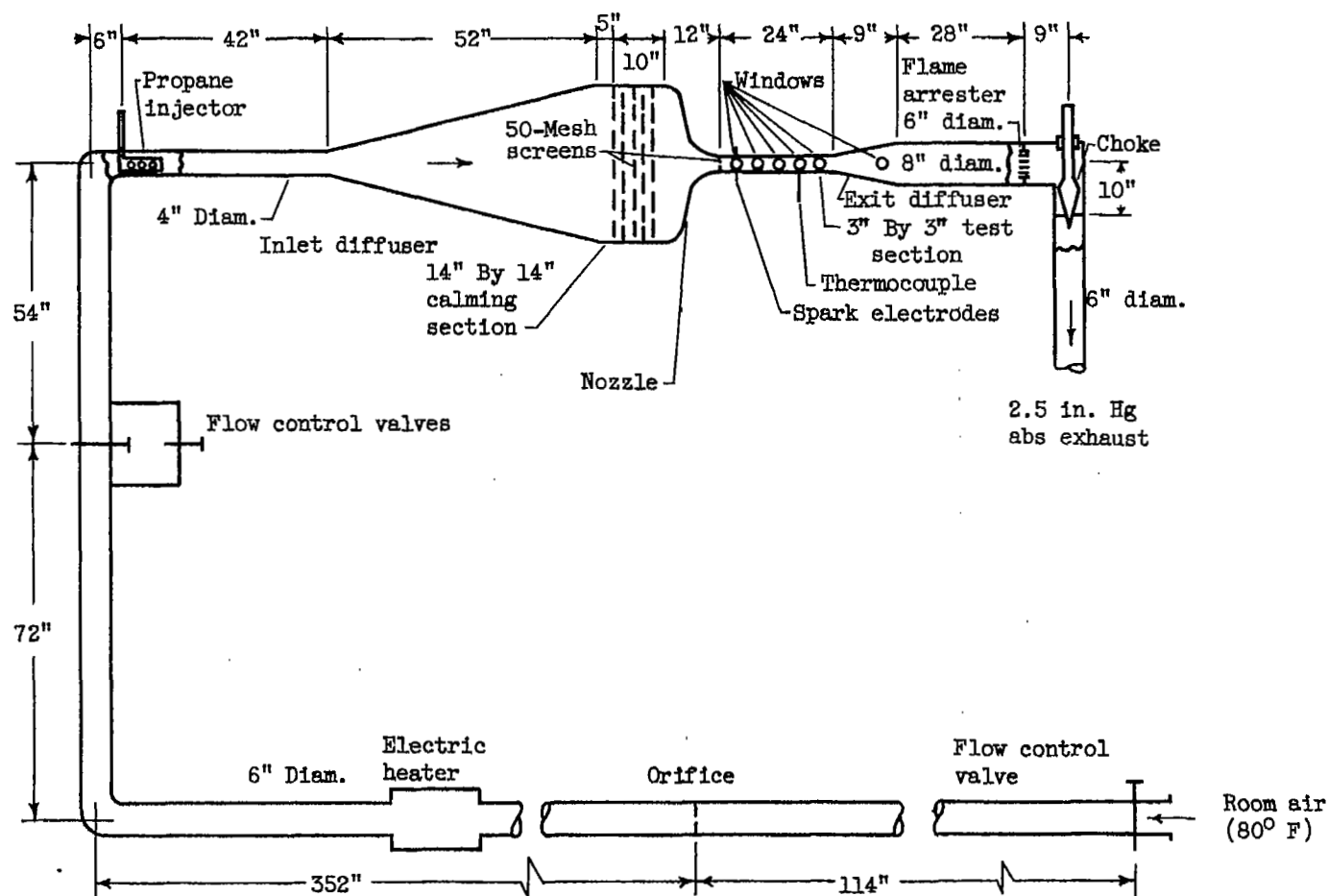
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Figure 1. - Apparatus used for determining effect of initial temperature and fuel-air ratio on spark ignition energy.
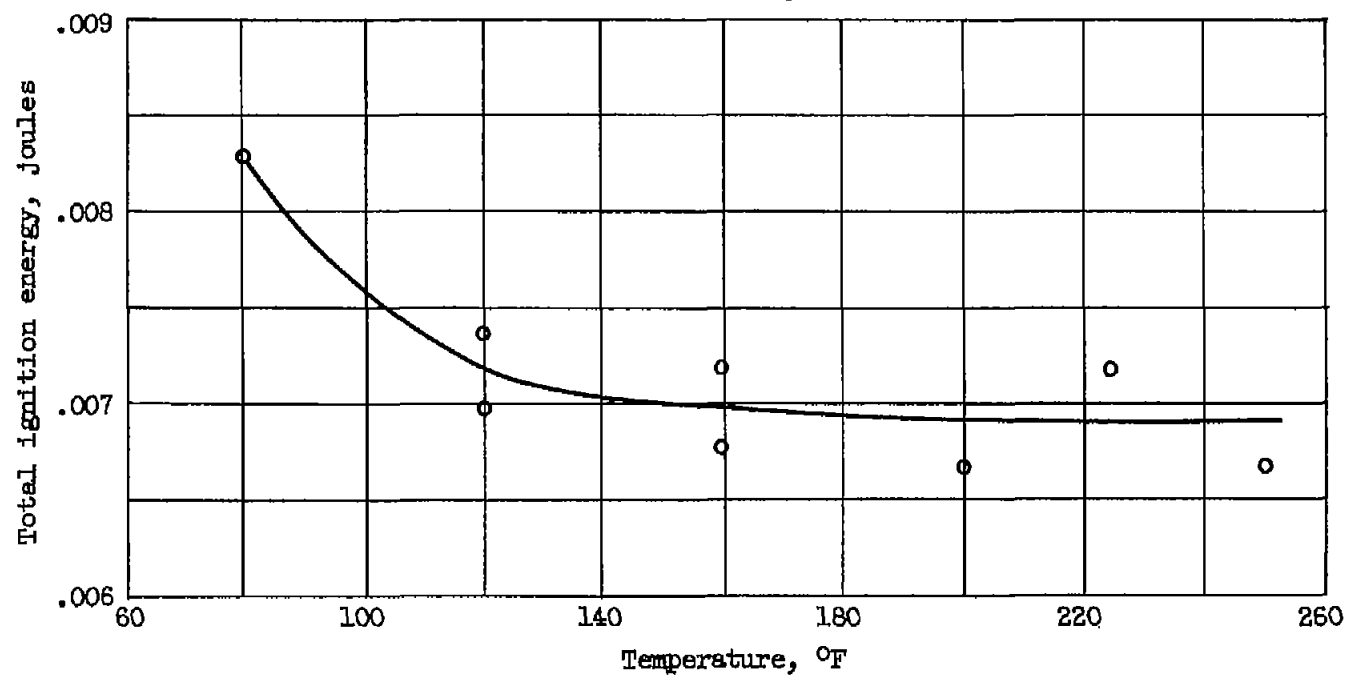
Figure 2. - Effect of initial temperature on total ignition energy. Pressure, 5.0 inches of mercury absolute; fuel-air ratio, 0.0835; gas velocity, 50 feet per second; electrode spacing, 0.37 inch; spark duration, 440 microseconds.
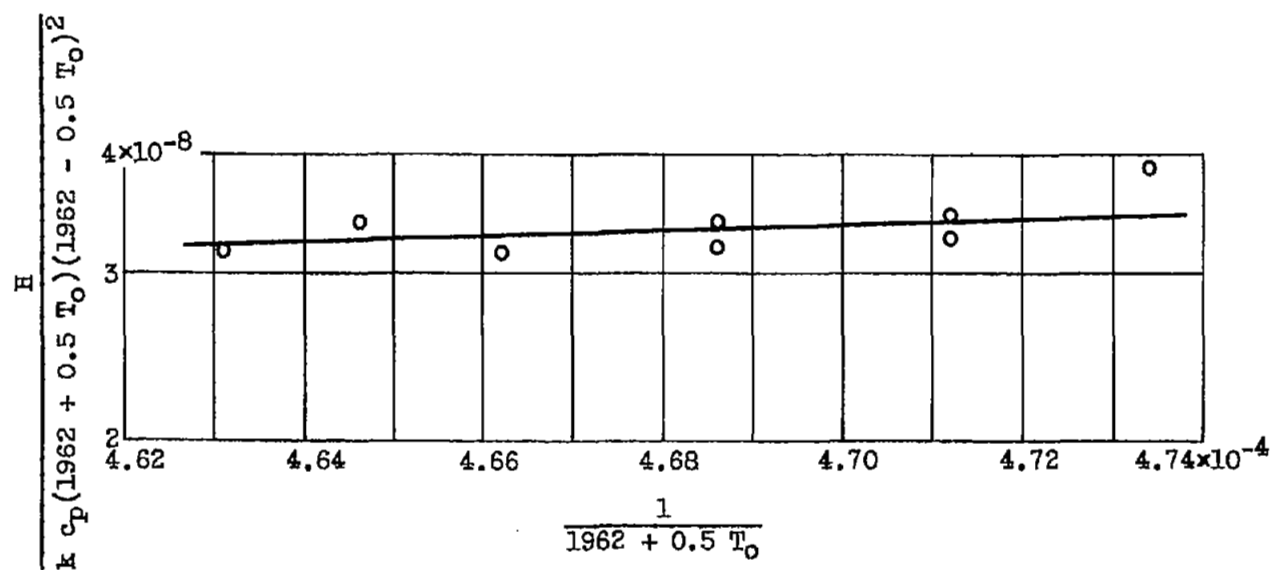
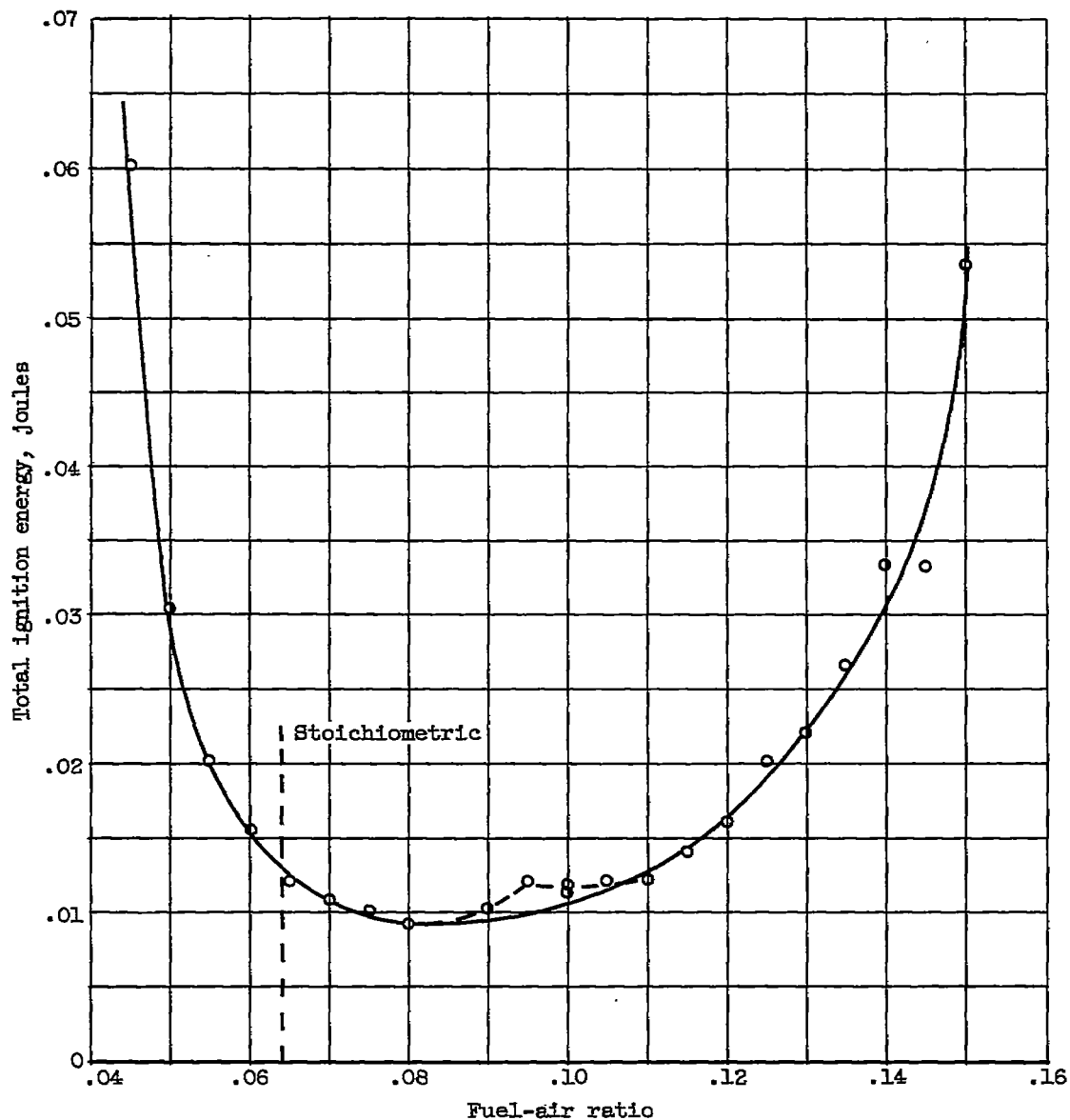Figure 3. - Correlation of ignition-energy data for a range of initial temperatures. (Data from fig. 2.)

Figure 4. - Effect of fuel-air ratio on total ignition energy.
Pressure, 5.0 inches of mercury absolute; gas velocity, 50
feet per second; temperature, 80° F; electrode spacing, 0.723
inch; spark duration, approximately 440 microseconds.
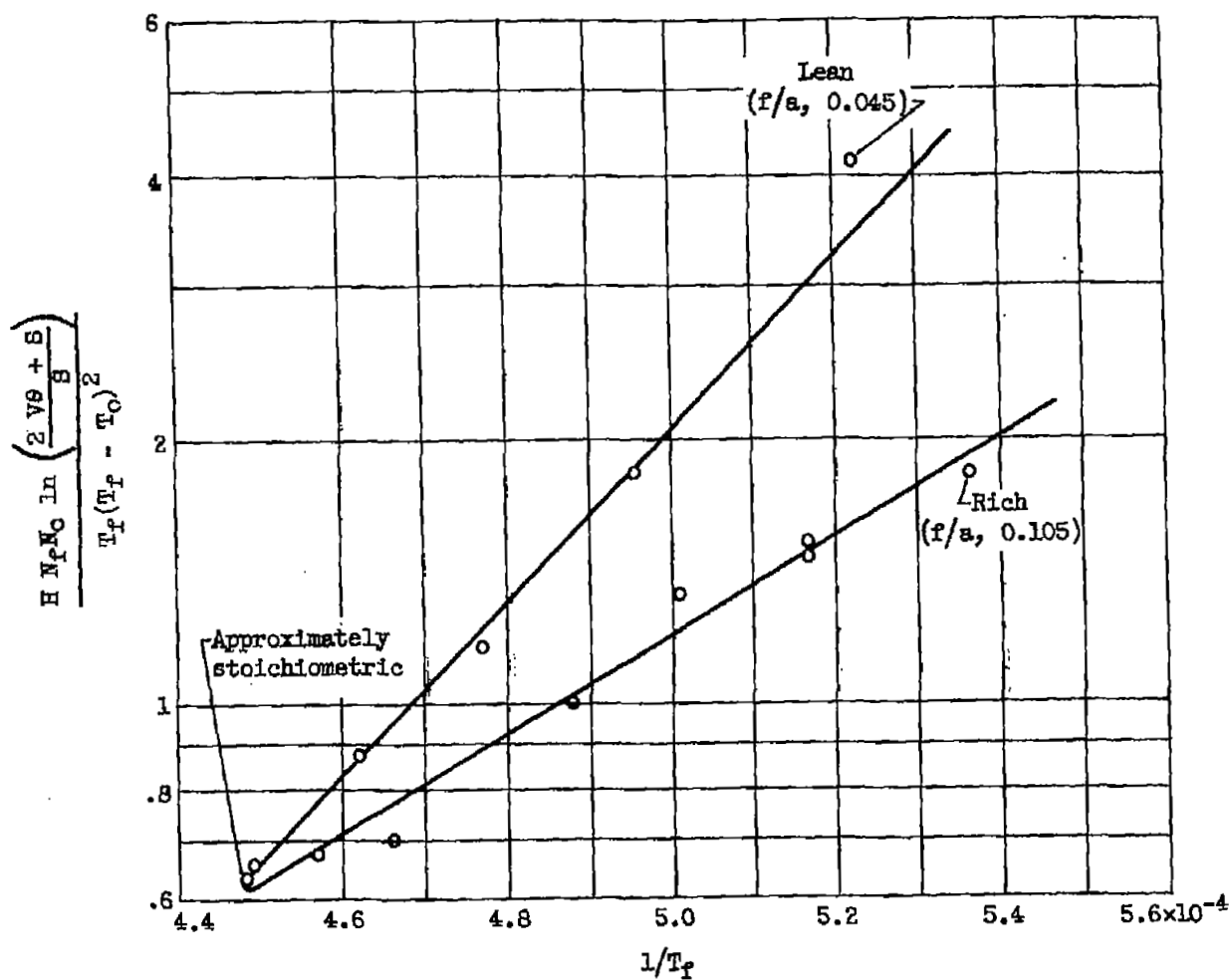
Figure 5. - Curve obtained by applying ignition-energy and fuel-air-ratio data to equation (4). Data (fuel-air ratio 0.045 to 0.105) from figure 4.
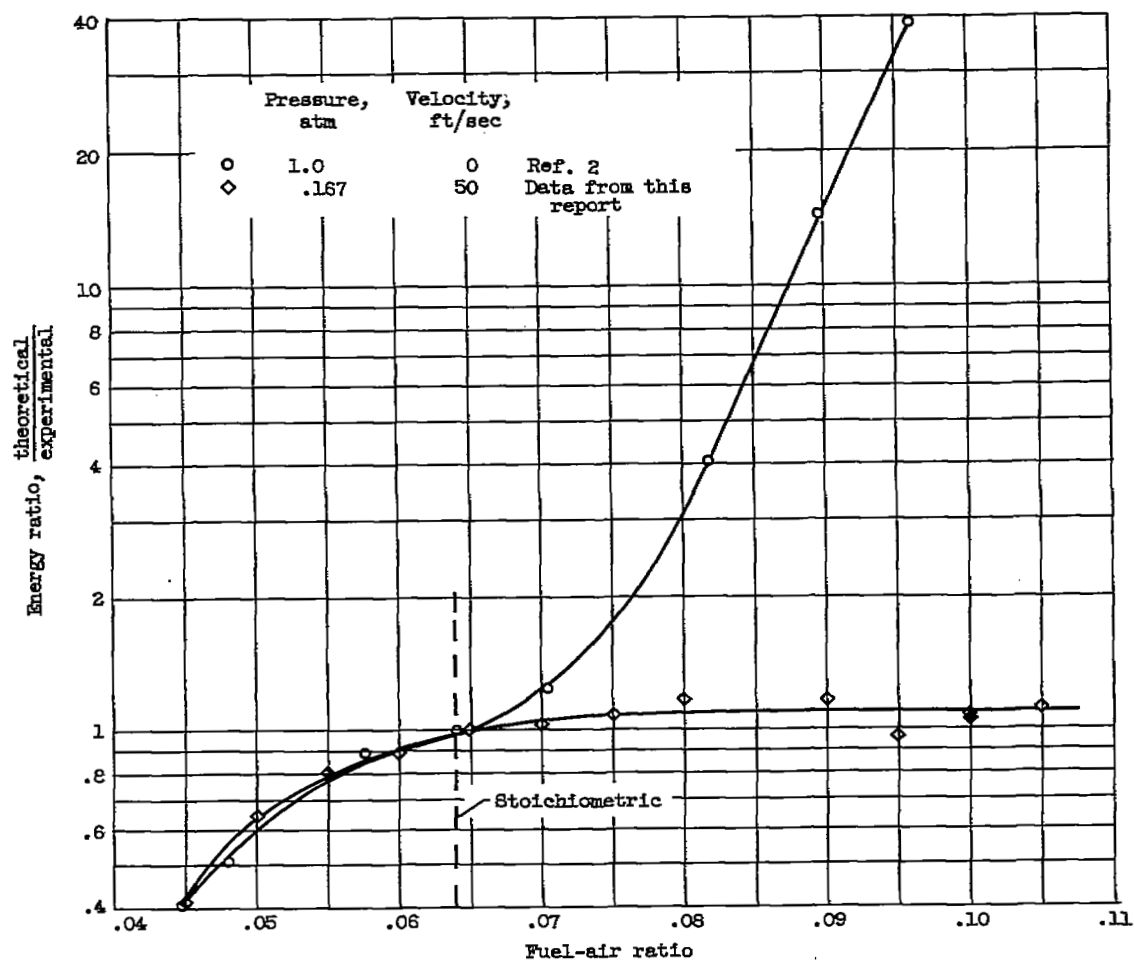
Figure 6. - Comparison of theoretical-to-experimental energy ratios with those of reference 2. Both sets of data adjusted to 1.0 at approximately stoichiometric fuel-air ratio.
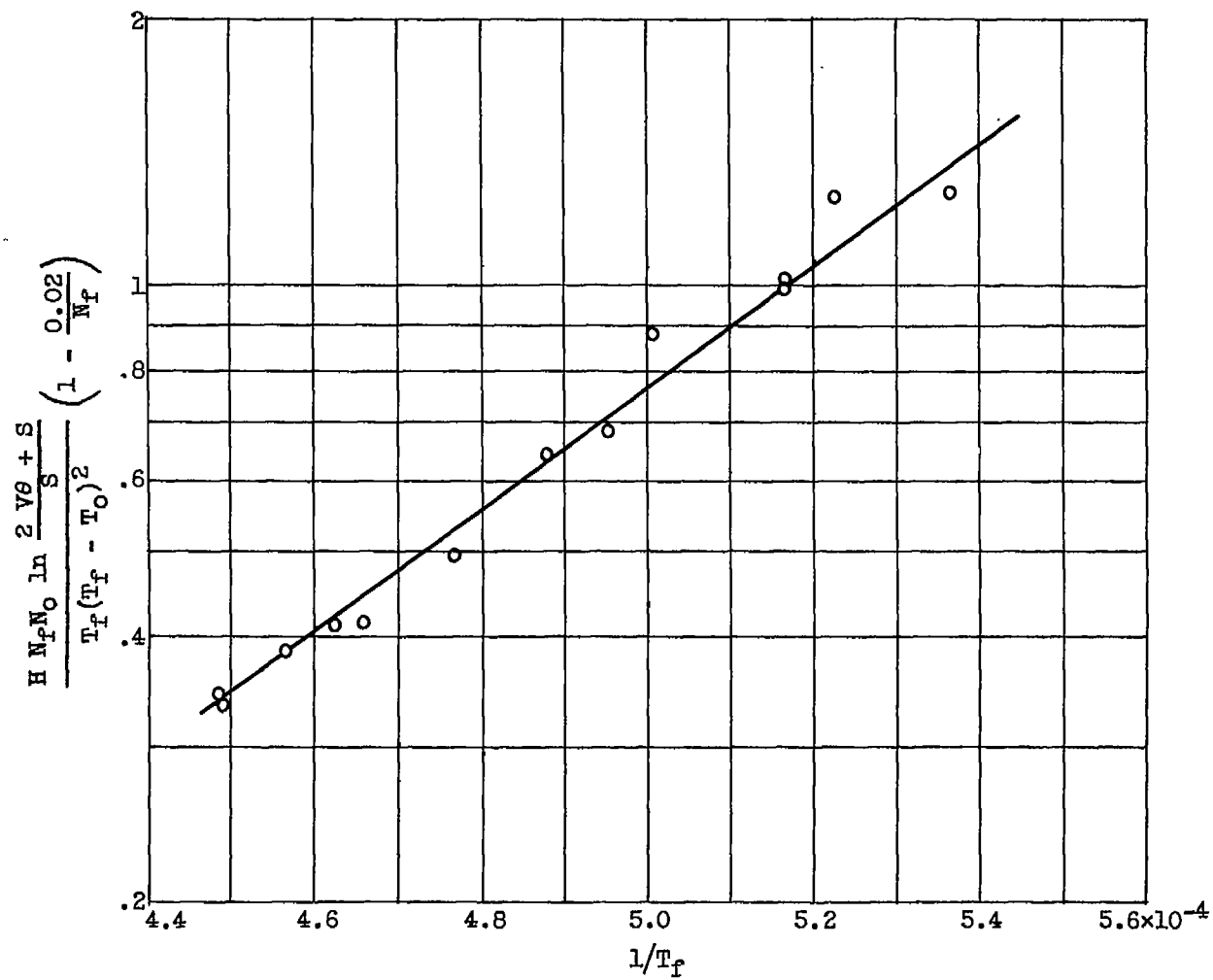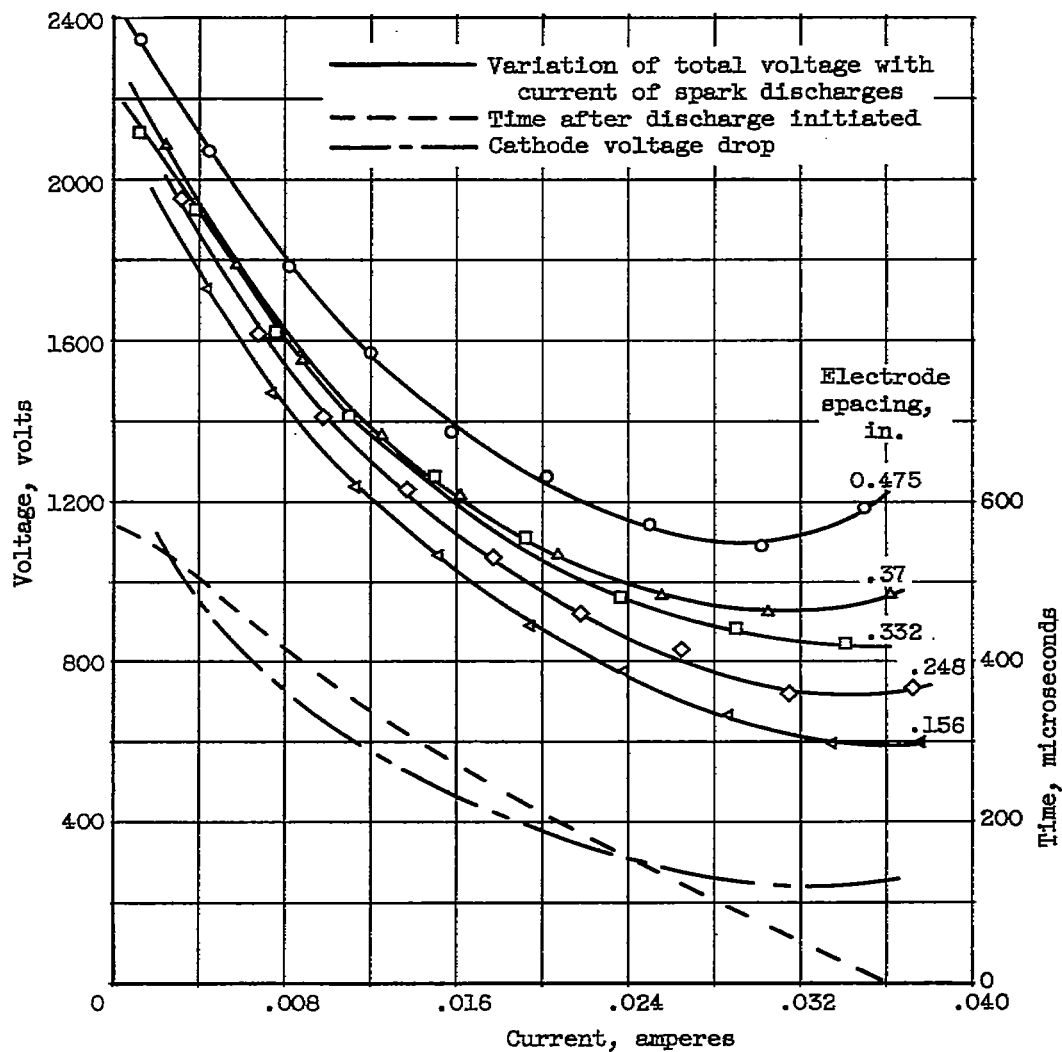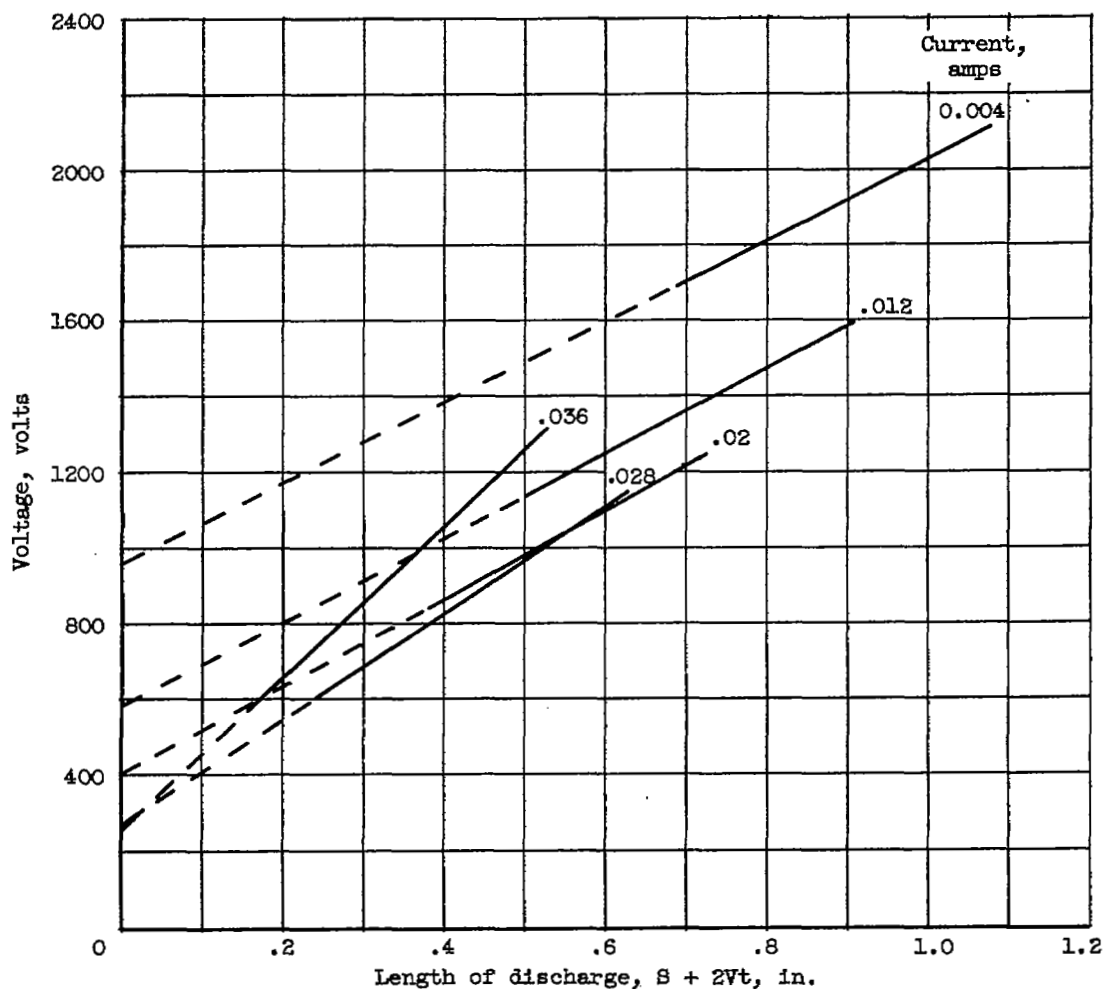
Figure 7. - Empirical correlation of ignition-energy data obtained over fuel-air-ratio range of 0.045 to 0.105.

(a) Variation of total voltage, cathode voltage, and time with
current of discharge.

Figure 8. - Example of determination of cathode energies. Pressure,
5.0 inches of mercury absolute; velocity, 50 feet per second; fuel-
air ratio, 0.10; temperature, 80° F.

(b) Constant-current cross plots of data. (S, electrode spacing;
V, velocity; t, time corresponding to current used.)

Figure 8. – Concluded. Example of determination of cathode energies.
Pressure, 5.0 inches of mercury absolute; velocity, 50 feet per sec-
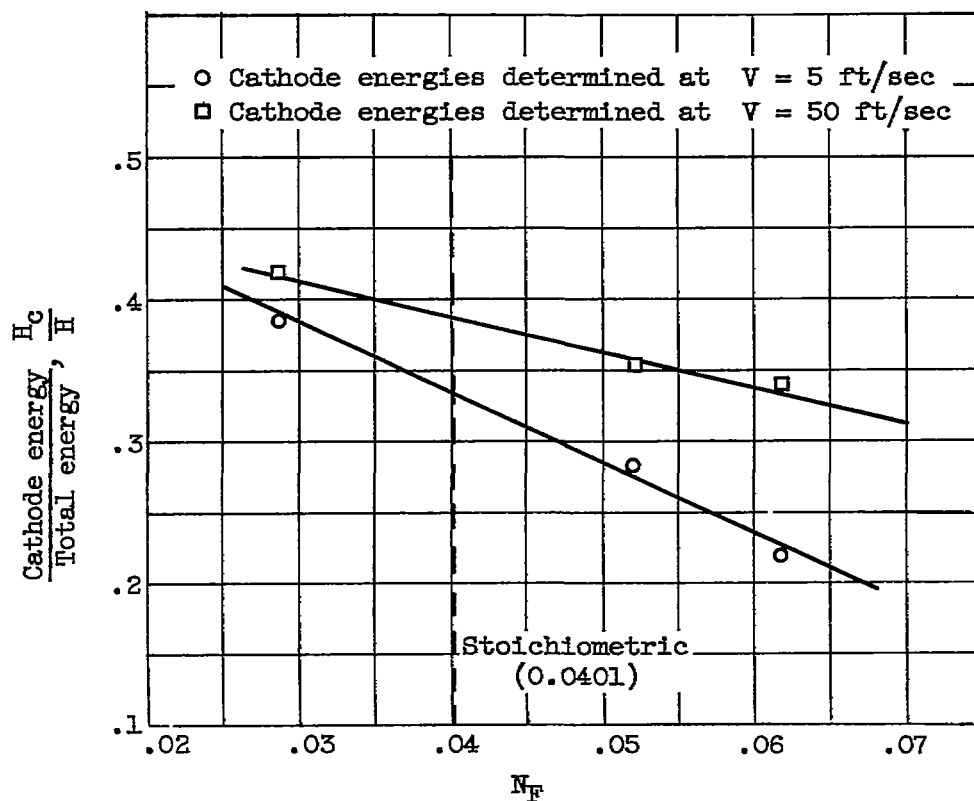ond; fuel-air ratio, 0.10; temperature, 80° F.

Figure 9. - Effect of fuel concentration on ratio
of cathode energy to total ignition energy.